Friction Stir Welding of Heat Resistant Ferritic Steels

著者	華 鵬
号	56
学位授与機関	Tohoku University
学位授与番号	工博第4658号
URL	http://hdl.handle.net/10097/61819

氏　　　　　名	ファ ペン 華　鵬
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指　導　教　員	東北大学教授　粉川　博之
論 文 審 査 委 員	主査　東北大学教授　粉川　博之　東北大学教授　古原　忠 東北大学教授　丸山　公一　東北大学准教授　佐藤　裕

論 文 内 容 要 旨

Chapter 1 Introduction

Heat resistant ferritic steel grades are highly valued materials for fabrication of components in thermal power generation industry due to their attractive combination of properties, i.e., excellent creep-rupture strength and good resistance to corrosion and oxidation. Currently, similar and dissimilar welding is used as major joining and repairing technology for the power plant components. However, conventional fusion weldability of the heat resistant ferritic steels is very poor, i.e., hydrogen-induced cracking, formation of delta ferrite, and solidification related defects (porosity, inclusions, etc) often occur during fusion welding processes. Additionally, dissimilar welding of the different heat resistant ferritic steels always leads to large residual stresses and formation of intermetallic compounds near the dissimilar interface, which are associated with different thermal properties and chemical interaction between the welded materials, respectively.

Friction stir welding (FSW), which was invented by The Welding Institute (TWI) in 1991, is a solid-state welding process, which uses an inconsumable welding tool consisting of a cylindrical shoulder and a profiled pin. Currently, FSW has been successfully applied to high-softening temperature materials (Fe, Ti) as well as low-softening temperature materials (Al, Mg). Due to the solid-state nature of FSW, it can avoid many problems associated with fusion welding processes. Since FSW is a relatively low heat-input process, it could be used for joining of dissimilar materials which cannot be welded through fusion processes. Furthermore, a severe plastic deformaion associated with friction stirring may be used to eliminate casting and forging defects in a material; this derivative technology is termed “friction-stir processing”. Therefore, it is expected that the application of FSW for manufacturing of the turbines can reduce production and repair costs, shorten delivery time, and increase efficiency and capacity of power plants.

Some previous studies dealt with FSW of 12Cr steel which is one of the major heat resistant ferritic steels for power plant application. They showed that FSW could produce defect-free weld in 12Cr steel, which suggests high potential of FSW for joining heat resistant ferritic steels. However, microstructure and properties, and their relationship of friction stir weld of 12Cr steel have not been fully understood. Moreover, similar and dissimilar FSW of the other heat resistant ferritic steels has not been examined.

In this study, feasibility of similar and dissimilar FSW of two heat-resistant ferritic steels of 12 Cr steel and 3.5NiCrMoV steel using polycrystalline cubic boron nitride (PCBN) tool was studied. These materials are used for fabrication of perspective turbine rotors in thermal power plants. Microstructure and mechanical properties of the obtained welds were systematically examined, and relationship between microstructure and properties was elucidated. Moreover, effect of the postweld heat treatment (PWHT) on the microstructure and properties was also studied, and optimal PWHT parameter for mechanical properties was obtained.

Chapter 2 Microstructure and hardness distribution in friction stir welded similar heat resistant ferritic steels

In this chapter, friction-stir weldability of two heat resistant ferritic steels, i.e., 12Cr steel and 3.5NiCrMoV steel, with thickness of 3 mm was studied. Microstructure in the weld was examined and the possible mcirostructual evolution during FSW was reconstructed. Mechanical properties of the weld were evaluated and the relationship between microstructure and properties was elucidated.

FSW trials were conducted in 12Cr-steel, consisting of tempered martensite microstructure with fine particles MX and coarse precipitates $M_{23}C_6$, at varied rotational speeds. Defect-free welds could be successfully produced at the rotational speeds of 400 and 800 rpm. The microstructural analysis showed that the peak temperature in the stir zone (SZ) during FSW exceeded the A_3 point, and thus the material experienced the martensitic transformation from the austenitic single phase structure. The fine particles MX were stably left during FSW, whereas the coarse precipitates $M_{23}C_6$ were dissolved. Formation of the quenched martensite with the MX particles significantly strengthened the SZ. The heat-affected zone (HAZ) contained both the tempered and quenched martensite, where hardness increased with increasing area fraction of quenched martensite.

FSW is also suitable for production of sound joints in 3.5NiCrMoV heat-resistant ferritic steel with the bainitic structure. The SZ had mixed microstructure consisting of bainite and quenched martensite, which implied that the peak temperature in the SZ during FSW exceeded the A_3 point. The HAZ also had the mixed microstructure consisting of bainite and quenched martensite, but it exhibited lower fraction of quenched martensite than the SZ. The hardness was significantly affected by area fraction of the quenched martensite in the weld.

Chapter 3 Microstructure and mechanical properties in friction stir welded dissimilar heat resistant ferritic steels

In this chapter, FSW was implemented for dissimilar joining of 12Cr and 3.5NiCrMoV heat resistant ferritic steels with thickness of 3 mm. Feasibility of dissimilar FSW of these steels was examined. Microstructure and mechanical properties of the dissimilar weld were discussed.

FSW was shown to be feasible to produce sound joints between the 12Cr steel and 3.5NiCrMoV steel. Each microstructure developed in the 12Cr and 3.5NiCrMoV parts of the dissimilar welds was found to be roughly similar to that evolved in each similar weld. FSW significantly increased the hardness in the weld and this effect was attributed to the formation of the quenched martensite. Significant variation in microhardness was found at the interface, which was hypothesized to be associated with the local diffusion of carbon from the 3.5NiCrMoV steel to the 12Cr steel during FSW. The tensile properties of the dissimilar weld were primarily governed by those of lowest hardness region, which corresponded to the HAZ near the base material (BM) on the 3.5NiCrMoV steel side.

Chapter 4 Postweld heat treatment of friction stir welded heat resistant ferritic steels

In this chapter, PWHT in the temperature range of 823-1023K was applied to the similar and dissimilar welds in an attempt to improve toughness of weld. Effect of PWHT on the structure and properties of the weld was examined.

It was found that the 12Cr-steel exhibits higher resistance to tempering than the 3.5NiCrMoV-steel. PWHT at higher temperatures than 973K resulted in significant microstructural changes in the 3.5NiCrMoV steel weld, which suggested that PWHT for this material (including similar ands dissimilar welds) should be performed at lower temperatures than 973K. The transverse tensile tests showed that the global mechanical properties of the dissimilar welds was usually governed by those of the region close to the base material on the 3.5NiCrMoV steel side; the dissimilar interface did not affect the mechanical properties. The small-punch (SP) test showed that the toughness of the friction-stir welded steels was significantly improved by the postweld heat treatment because of the martensite tempering. The optimal temperature for the annealing was established to be about 873K.

Chapter 5 Conclusions

This chapter is a summary of the results presented from chapter 2 to chapter 4, and the general conclusions can be presented as follows.

FSW is feasible for similar and dissimilar joining of heat-resistant ferritic steels. The typical defects associated with conventional fusion welding including hydrogen-induced cracking, solidification cracking, and formation of delta ferrite and intermetallic compounds were not detected in the similar and dissimilar welds.

The microstructual evolution in similar and dissimilar welds is elucidated on the basis of the comprehensive microstructural observations, analysis of continuous cooling transformation (CCT) diagrams, and simulation of the FSW thermal cycle. It was deduced that the peak temperature during FSW exceeded the A_3 point and therefore the formation of the final stir zone structure was governed by martensite phase transformation. The formation of the quenched martensite significantly increased material strength but deteriorate its toughness.

However, subsequent PWHT of the welds at suitable temperature leads to tempering of martensite and thus improves the toughness of the welds. This suggests that the mechanical properties of similar and dissimilar friction stir welds of heat resistant ferritic steels can be modified by PWHT.

論文審査結果の要旨

フェライト系耐熱鋼は優れた耐クリープ特性と耐腐食性を有し、発電プラントのタービンロータ等に利用されている。フェライト系耐熱鋼の多くは溶融溶接性に劣るため、一般に溶接施工は行われないが、補修溶接や異鋼種接合が可能になれば、部品の長寿命化および低コスト化が可能となる。溶融溶接時の問題は高入熱もしくは溶融・凝固に起因するため、低入熱の固相接合法である摩擦攪拌接合の適用により防止・低減が期待される。本研究では、代表的なフェライト系耐熱鋼である 12Cr 鋼と 3.5NiCrMoV 鋼を対象として、同鋼種接合と異鋼種接合を摩擦攪拌接合により実施し、フェライト系耐熱鋼に対する摩擦攪拌接合の適用可能性、ミクロ組織と機械的特性の関係、同鋼種継手と異鋼種継手に対する接合後熱処理の影響を明らかにすることを目的としている。論文は全編５章で構成されている。

第１章は序論であり、本研究の背景および目的を述べている。

第２章では、12Cr 鋼と 3.5NiCrMoV 鋼の同鋼種接合性と同鋼種継手におけるミクロ組織と硬さ分布の関係をそれぞれ調べている。まず、フェライト系耐熱鋼の摩擦攪拌接合が可能であることを示している。また、いずれの鋼種においても、摩擦攪拌接合により硬さの上昇が見られ、これは接合過程に生成した焼入れマルテンサイトの量により説明できることを明らかにしている。

第３章では、12Cr 鋼と 3.5NiCrMoV 鋼の異鋼種接合性と異鋼種継手のミクロ組織と機械的特性の関係を調べている。まず、フェライト系耐熱鋼の異鋼種摩擦攪拌接合が可能であることを示している。攪拌部では両鋼種領域が個々にジグザグ状界面を挟んで存在し、それぞれの鋼種領域のミクロ組織と硬さは同鋼種継手のものと同じであることから、摩擦攪拌接合による両鋼の混合は生じないことを明らかにしている。また、継手引張試験による破断は、異鋼種継手の最軟化部である 3.5NiCrMoV 鋼側の熱影響部で生じるため、接合界面は機械的特性に悪影響を及ぼさないことを明らかにしている。

第４章では、同鋼種継手および異鋼種継手のミクロ組織および靭性に及ぼす接合後熱処理の影響を調べている。接合後熱処理により、同鋼種継手および異鋼種継手の攪拌部では焼入れマルテンサイトの焼戻しが起こり、攪拌部の靭性が向上することを明らかにしている。

第５章は本研究の結果をまとめた総括である。

以上要するに本論文は、フェライト系耐熱鋼摩擦攪拌接合部におけるミクロ組織と機械的特性の関係を明らかにしたものであり、材料システム工学の発展に寄与するところが少なくない。

よって、本論文を博士（工学）の学位論文として合格と認める。